Motivation
for a range of
Ultrafast X-Ray Sources

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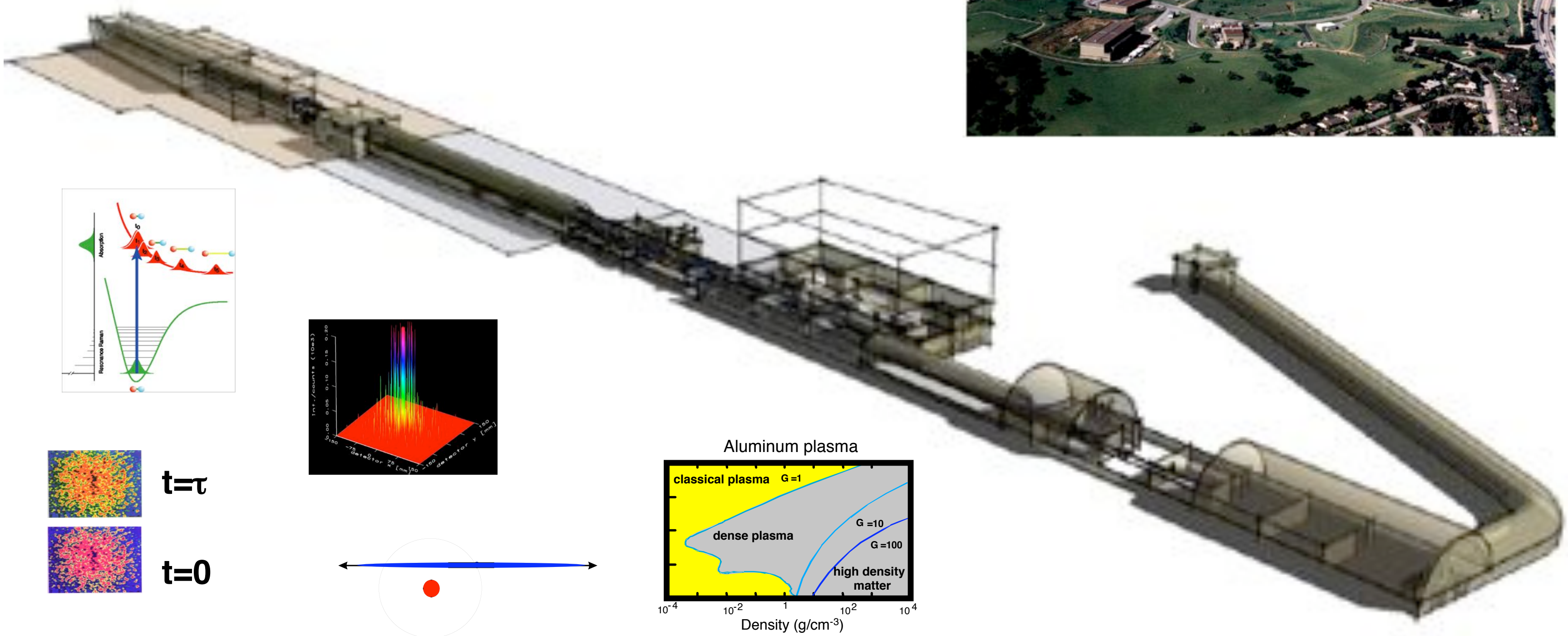
Short Pulse X-Rays at the APS 5/9/08

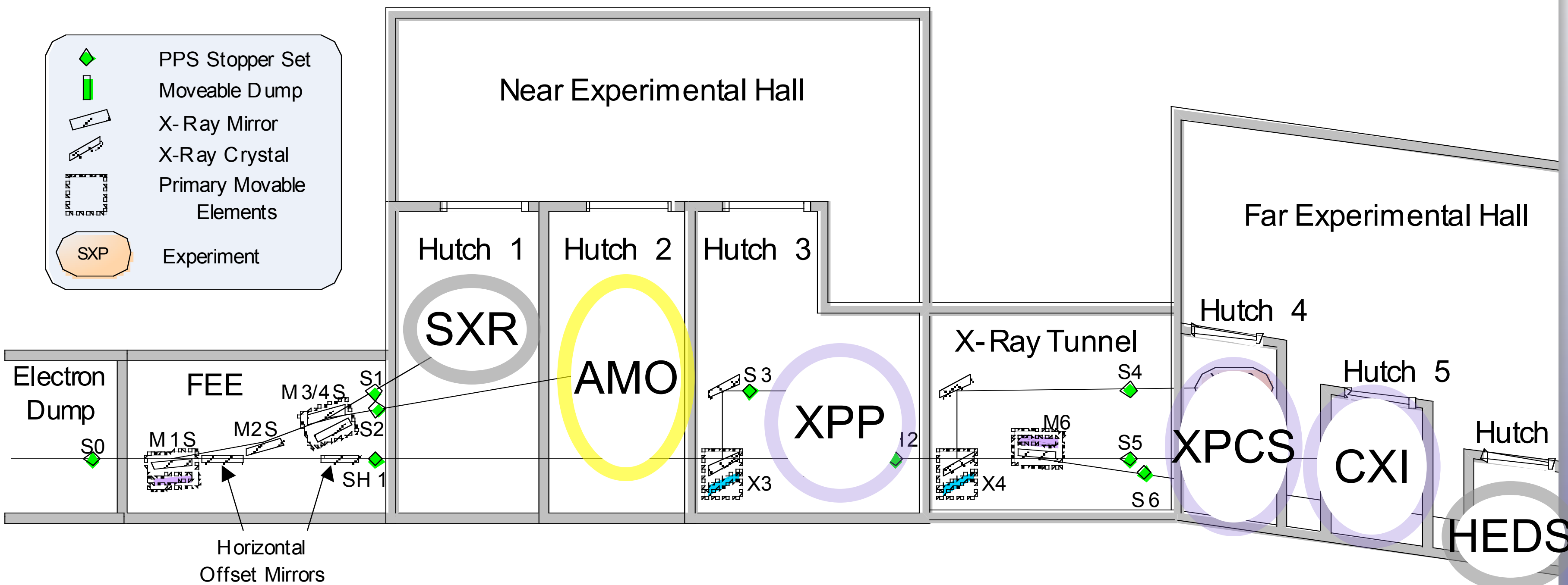
Observations on ultrafast x-ray science

- workshops and reports, along with successful operation of new sources at APS, ALS, BESSY, SLS, SPPS, FLASH, etc., indicate that compelling ultrafast x-ray science will be enabled by accelerator-based sources
- several new x-ray FELS will soon become available
- optical lasers with high-harmonic-generation and phase-stabilization have indicated the potential of ultrafast, short-wavelength science
- various proposals exist for R&D and construction of new ultrafast x-ray sources, using crabing, slicing, seeded-FELs, ERLs, lasers, etc.
- high peak and average power lasers will be available for manipulating electron beams and seeding FELs, but accelerator-based x-ray sources have unique capabilities beyond x-ray harmonics of lasers

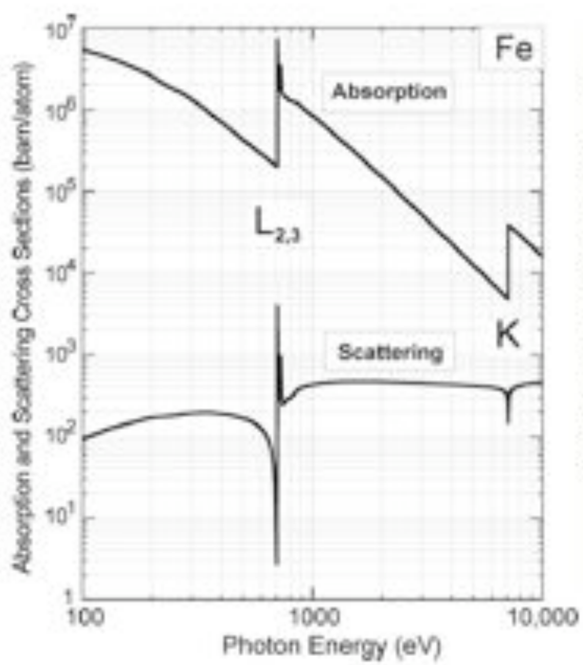
LCLS will enable a range of x-ray science beginning 2009-10

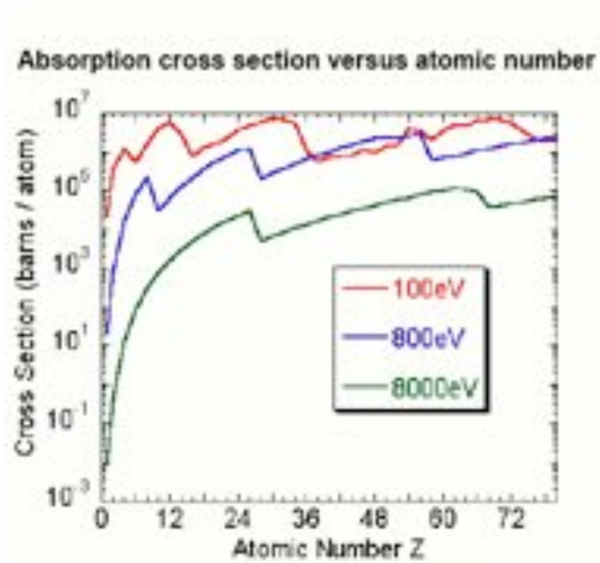


Near and Far Experimental Hall Hutches for LCLS



Potential issue: excitation or damage of sample during probing of condensed matter by soft x-ray FELs





$\gamma \sim 10^9$ W @ 30 fs @ 600 eV = 3×10^{11} photons

$A \sim (1 - 100\ \mu m)^2$

$\sigma \sim 10^{-18}\ cm^2$

N* / N = 0.1 - 100%

… concerns from Jo Stohr, others

…so how many x-rays are too much or too little ?

- Spontaneous sources

  Synchrotron slicing = 10^2 - 10^4 photons/pulse at 1-10 kHz

  Synchrotron crabing = 10^4 - 10^6 photons/pulse at 6 MHz

  SPPS = 10^8 photons/pulse at 10 - 100 Hz

- FELs

  LCLS = 10^{12} photons at 120 Hz

  GW peak power

- Laser harmonics

  10^{-6} conversion in peak and average power (MW peak / μW average)

A range of new sources and clever techniques are needed

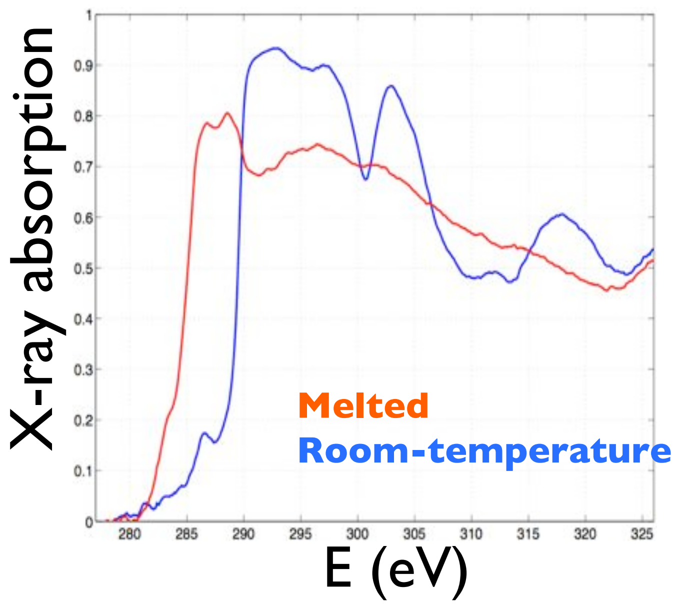
- amplification of scattering by use of crystals
- dispersive spectroscopy for parallel measurements
- zone plate optics, better detectors, PEEM, diffractive imaging

Recent Berkeley Workshop
"Science for a New Class of Soft X-ray Light Sources"

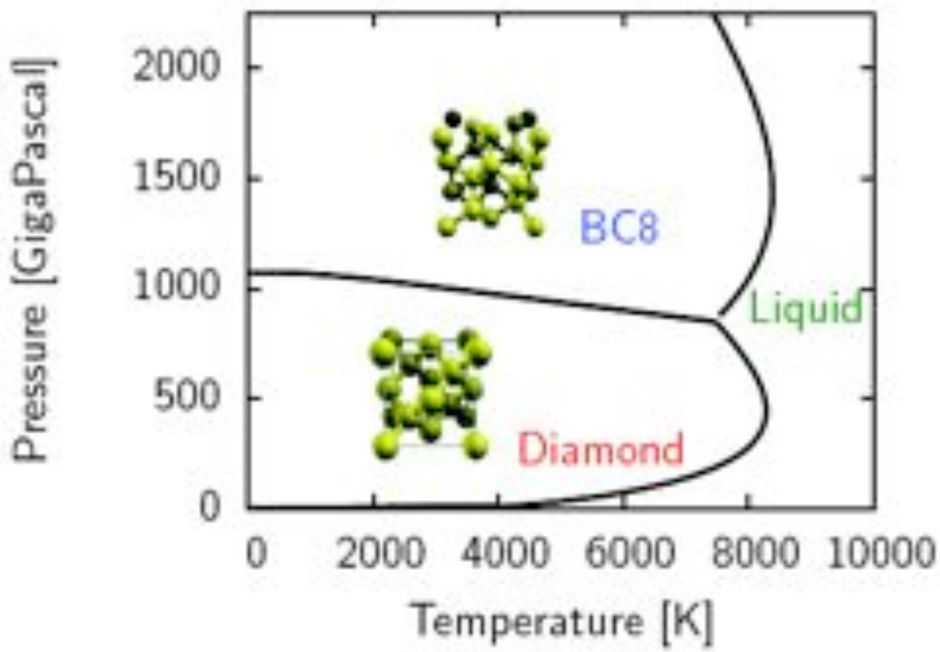
Focused on 5 areas:

1. Atomic, Molecular and Optical Physics
2. Chemical Physics
3. Correlated Materials
4. Magnetization and Spin Dynamics
5. Nanoscience and Coherence

Example of dynamic SXR spectroscopy: K-edge absorption of high-T liquid carbon

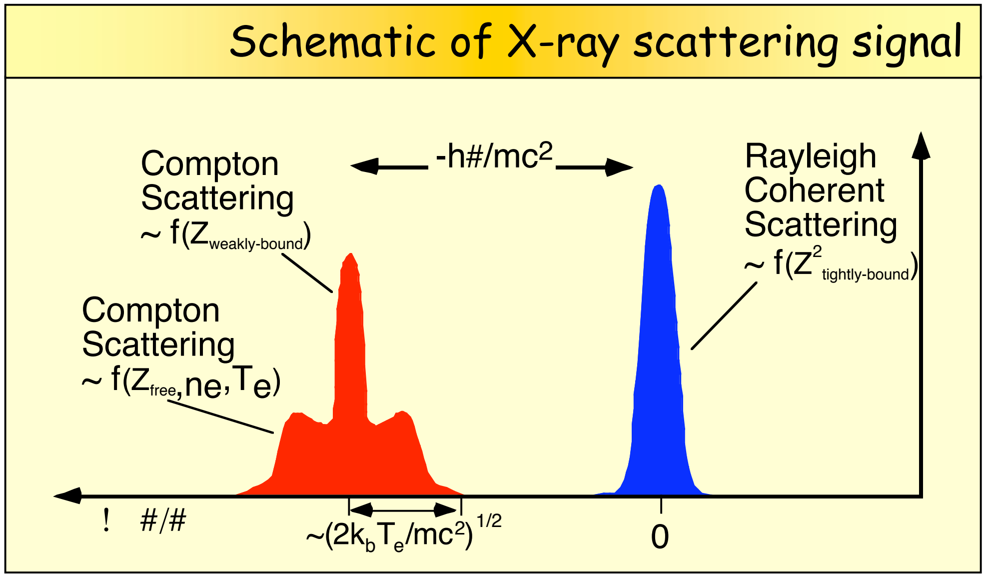


Heimann, et al



Correa, et al

Inelastic hard x-ray scattering measures dynamic density and temperature



From scattering intensities, we determine:

- electron motion
- collective motion (plasmons, ion acoustic wave)
- free and bound electrons
- screening and collisions

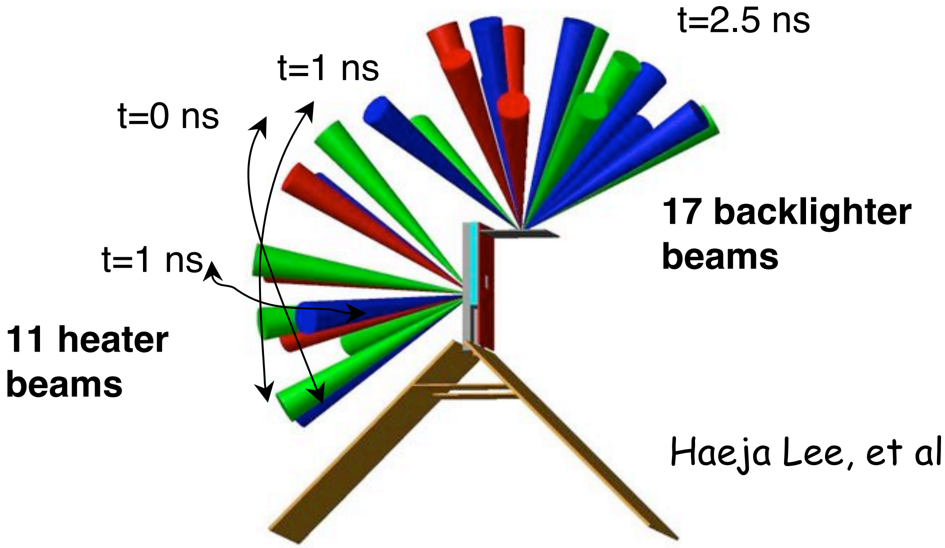
By varying the scattering angle, we determine:

- collective modes and non-collective behavior

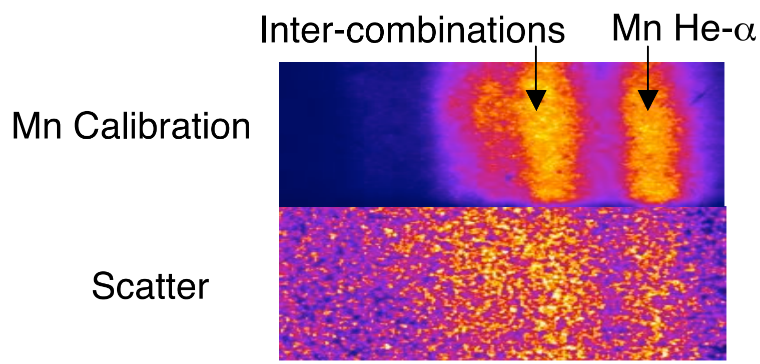
X-ray Thomson scattering uses x-ray backlighters to study compressed Be

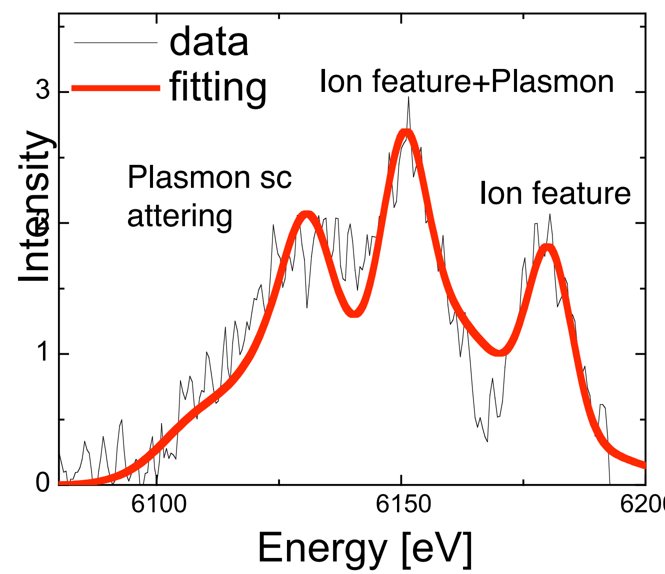
Laser plasma x-ray source

used to measure x-ray scattering on compressed Be



Haeja Lee, et al



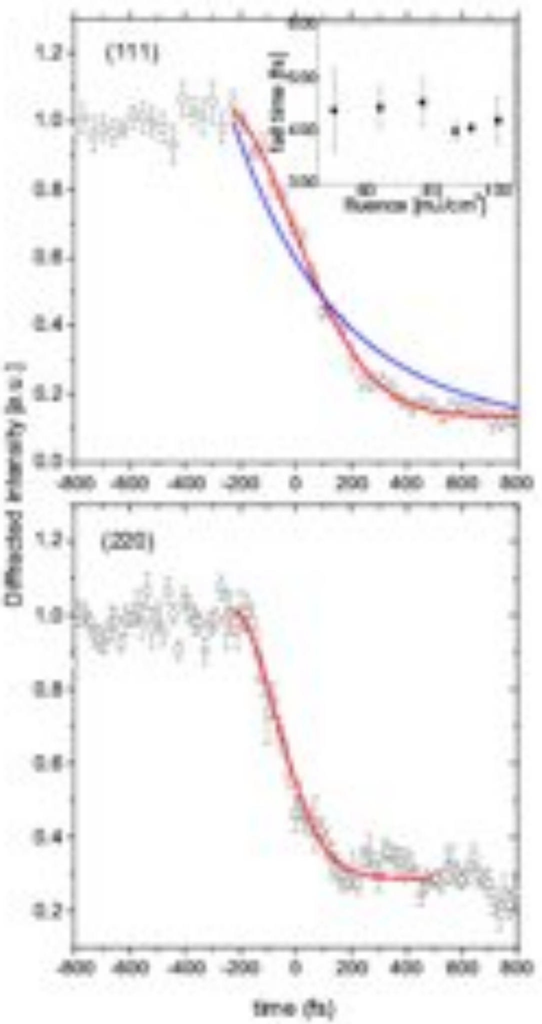


- **measured plasmon scattering from shock compressed Be**
- **position of the plasmon resonance yields density**

n_e=1×10^{23} cm^{-3}, T_e=10 eV at 3 ns

Glenzer, Lee, Falcone, et al

Disordering of a lattice through bond-breaking observed at short times through 8 keV diffraction changes at the SPPS



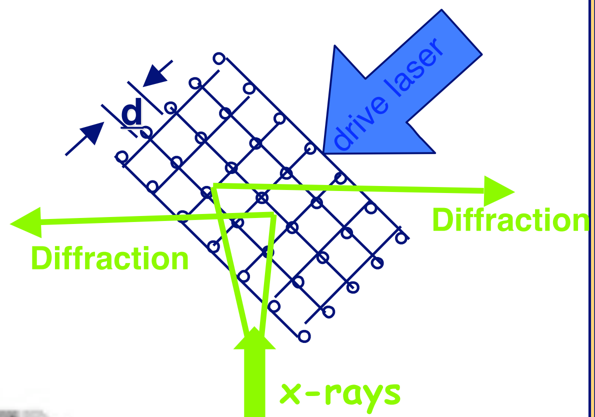
- (111) and (220) reflections measured
- non-thermal melting observed
- more complex system will require more photons

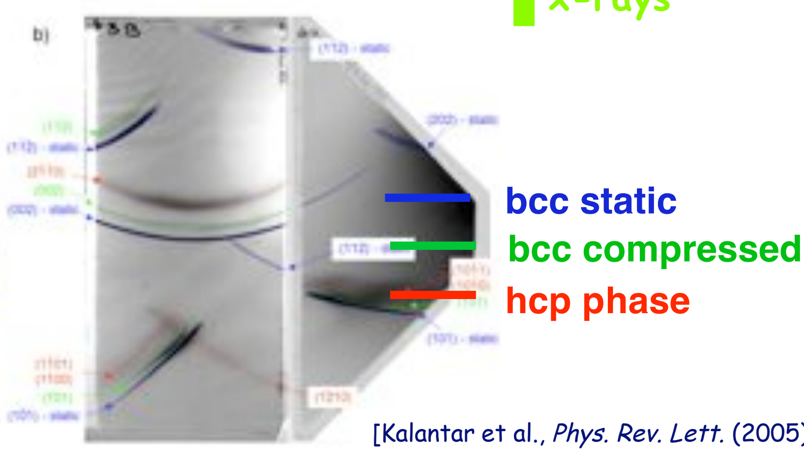
SPPS Collaboration

Intense x-ray fluxes from LCLS will enable real-time *in situ* measurements of microstructure evolution at high pressure

What is the timescale of the bcc-hcp phase transformation in Fe?

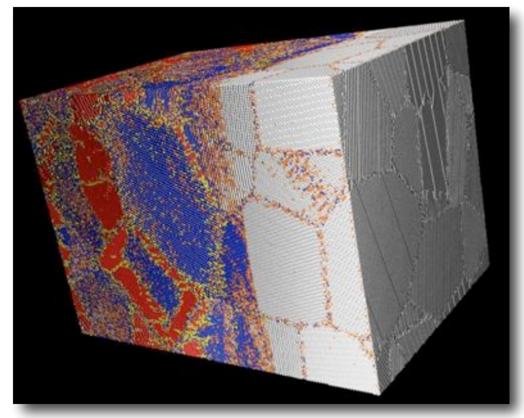
Current measurement limited to timescales >> psec



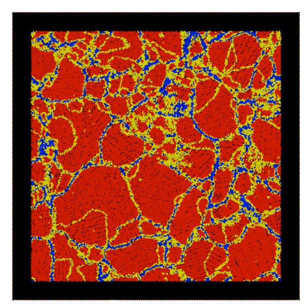


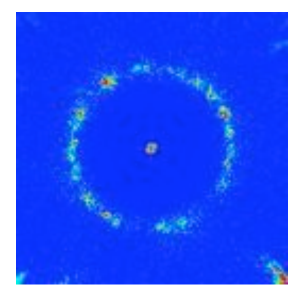
[Kalantar et al., *Phys. Rev. Lett.* (2005)]

Simulations predict subpicosecond phenomena observable using LCLS



Kadau et al., *Science* (2002).





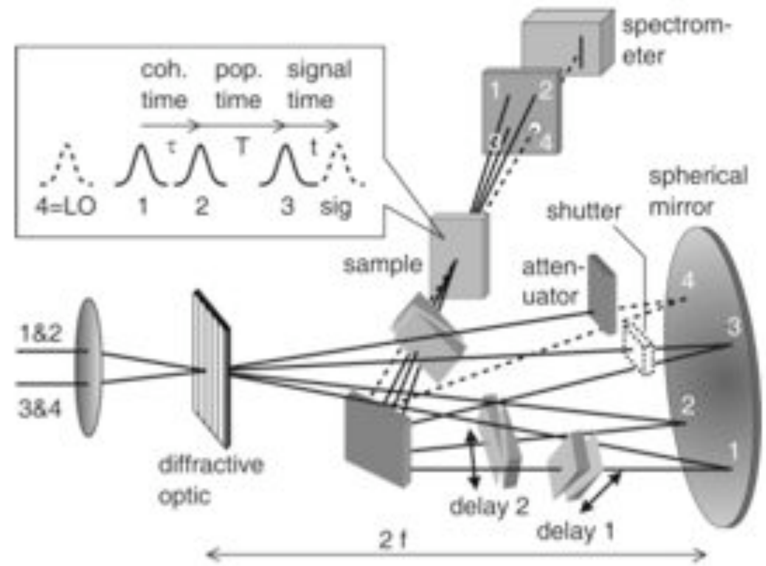
Atomic, Molecular and Optical Physics
and
Chemical Physics Breakouts

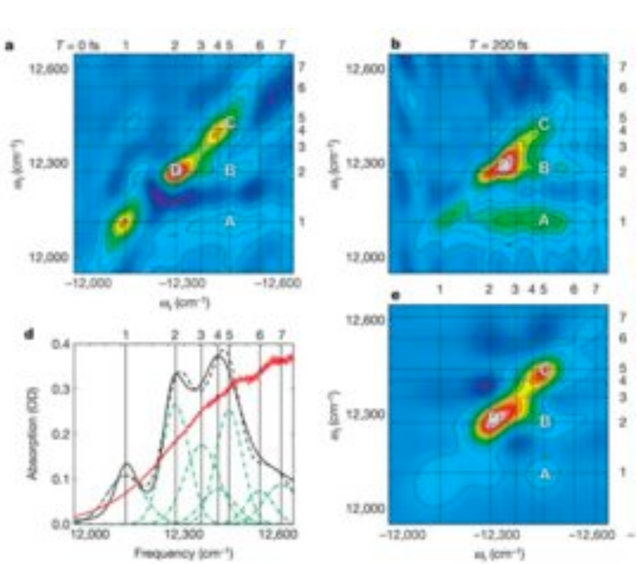
- attosecond electron dynamics
- probe and control of electron correlation
- evolution of excited state dynamics in the gas phase
- extreme non-Born-Oppenheimer chemistry
- non-adiabatic control schemes
- 2-d x-ray correlation spectroscopy

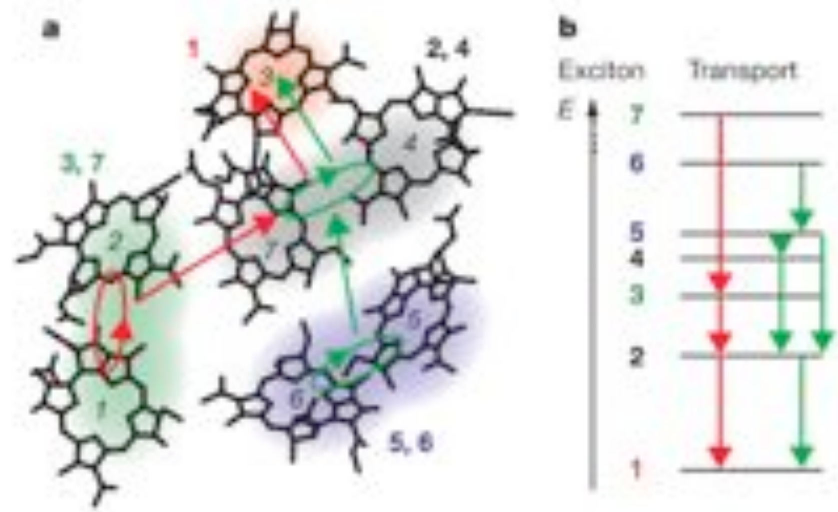
Two-dimensional spectroscopy of electronic couplings in photosynthesis

Tobias Brixner[1], Jens Stenger[1], Harsha M. Vaswani[1], Minhaeng Cho[2], Robert E. Blankenship[3] & Graham R. Fleming[1]

[1]Department of Chemistry, and the Institute for Quantitative Biomedical Research (QB3), University of California, Berkeley, and Physical Biosciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[2]Department of Chemistry and Center for Multidimensional Spectroscopy, Division of Chemistry and Molecular Engineering, Korea University, Seoul 136-701, Korea
[3]Department of Chemistry and Biochemistry, Arizona State University, Tempe, Arizona 85287, USA





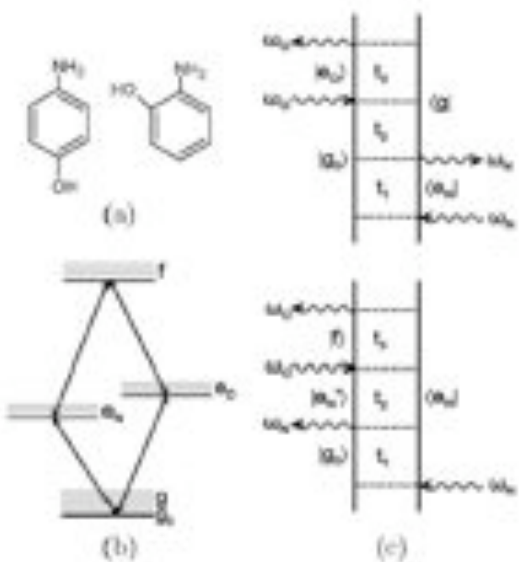


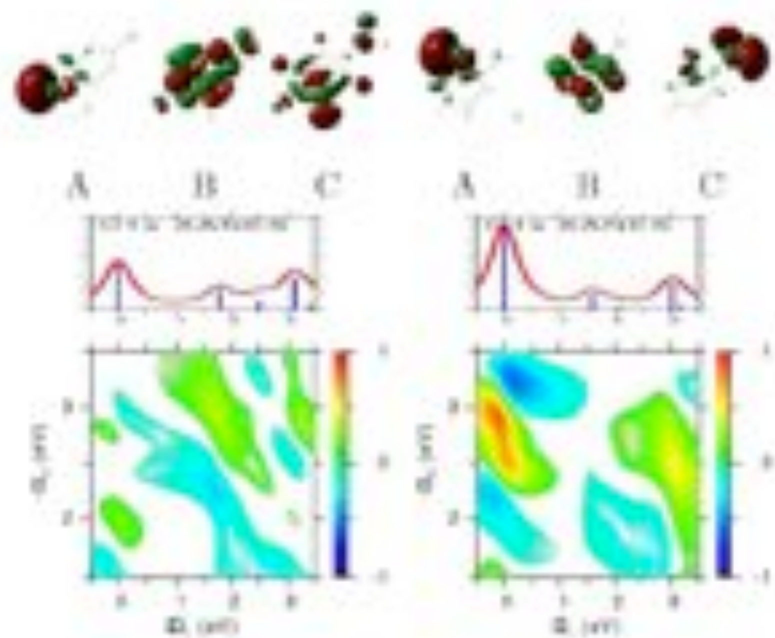
Coherent ultrafast core-hole correlation spectroscopy; x-ray analogues of multidimensional NMR

Igor V. Schweigert and Shaul Mukamel
Department of Chemistry, University of California, Irvine, California 92697-2025

We propose two dimensional x-ray coherent correlation spectroscopy (2DXCS) for the study of interactions between core-electron and valence transitions. This technique might find experimental applications in the future when very high intensity x-ray sources become available. Spectra obtained by varying two delay periods between pulses show off-diagonal cross-peaks induced by coupling of core transitions of two different types. Calculations of the N1s and O1s signals of aminophenol isomers illustrate how novel information about many-body effects in electronic structure and excitations of molecules can be extracted from these spectra.

PACS numbers: 33.20.Rm, 42.65.Re





Workshop Conclusions "Science for a New Class of Soft X-ray Light Sources"

- Function relies on structure, bonding, and dynamics
  - soft x-rays reveal bonding and structure
  - hard x-rays reveal atomic positions

- Energy and information flow utilize ultrafast timescales
  - beat timescales for dissipation
    e.g., vision, photosynthesis
  - allow multimode excitation to dissipate energy
    e.g., DNA, damage
  - speed, competing rates, and quantum pathways
    critical to functional optimization

- Coherent radiation implies longitudinal and transverse coherence for
  - high resolution spatial imaging and spectroscopy
  - high peak and high average power for non-linear measurements

- Imaging matter and energy flow will utilize additional IR to x-ray radiation

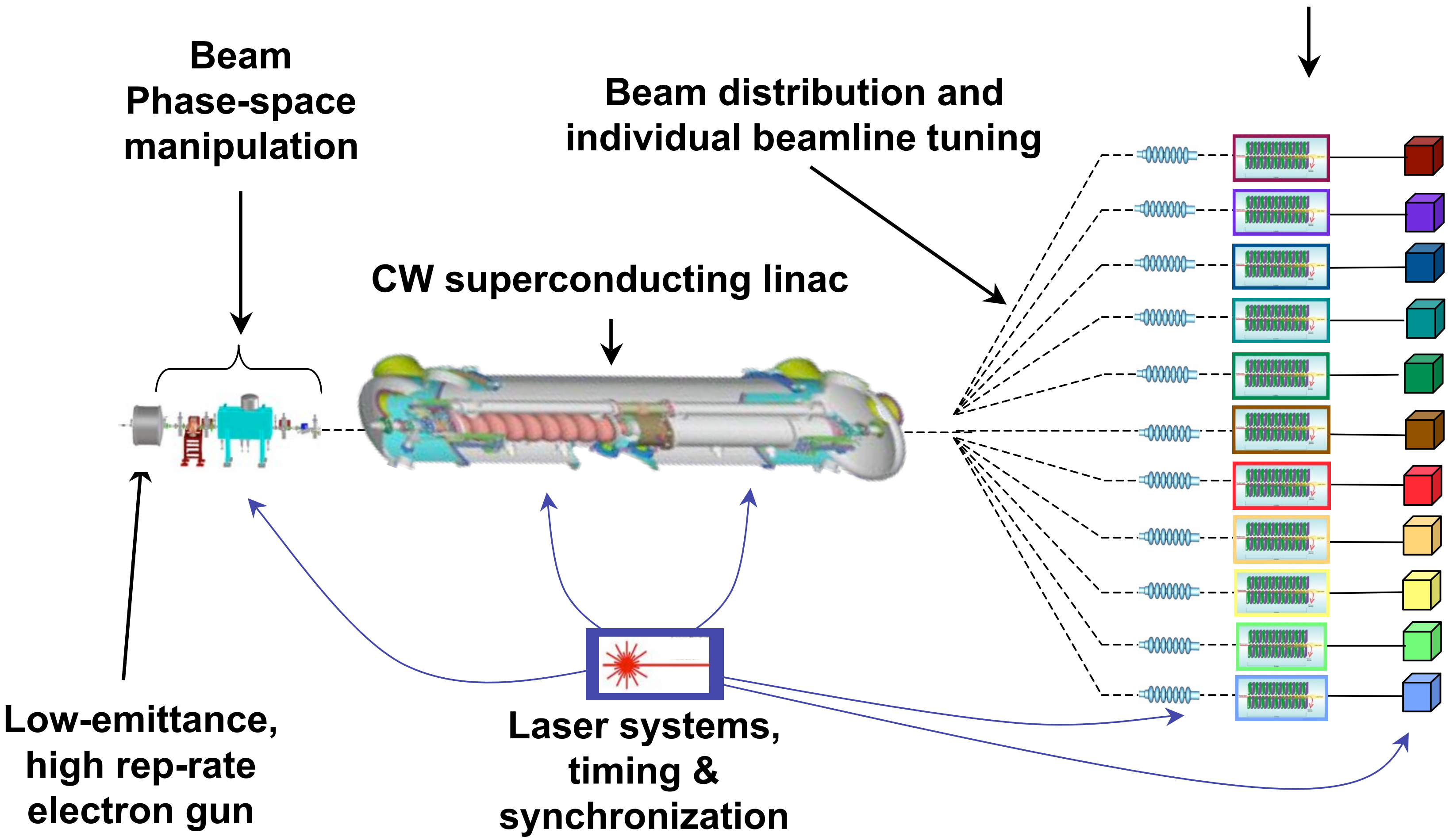
Requirements for new light sources are challenging

- **Tunable**
  - Spectroscopy, imaging, and near resonance scattering
- **Selectable pulse length**
  - Attosecond science for timescales of electron-electron correlation
  - Longer (time-BW-limited) pulses required for high resolution
- **Selectable pulse energy and repetition rate**
  - Maximize data and S/N, and minimize damage
- **Multiple wavelengths and precision delays**
- **Beam quality**
  - Coherence and stability
- **Amplitude and phase controlled pulses**
- **Synchronized pumps**
  - THz, IR, optical, magnetic - to drive non-equilibrium structures
  - Pressure, temperature, electronic, and phonon excitation beyond ambient
- **Induce nanoscale structure with transient gratings**

A vision for a future light source facility

HIGH REP-RATE, SEEDED, VUV — SOFT X-RAY FEL ARRAY

- Independent array of configurable FELs
- Control of electrons: seeded, attosecond, ESASE
- Control of x-rays: wavelength, pulse duration, polarization



Performance goals of a SXR FEL

FELs WITH THREE MODES OF OPERATION

	Short-pulse beamlines	High-resolution beamlines	Sub-femtosecond beamlines
Wavelength range (nm)	~200 – 1	~200 – 1	~40 – 1
Photon energy (eV)	6 – 1240	6 – 1240	30 – 1240
Repetition rate (kHz)	100	100	1-100
Peak power (GW)	1	1	0.1 – 0.3
Photons/pulse (@1 nm)	$5x10^{11}$ (in 100 fs)	$2.5x10^{12}$ (in 500 fs)	$1.5x10^{8}$ (in 100 as)
Timing stability (fs)	10	10	TBD
Pulse length (fs)	1 – 100	100 – 1000	0.1 - 1
Harmonics	! few%	! few%	! few%
Polarization	Variable, linear/circular	Variable, linear/circular	Variable, linear/circular

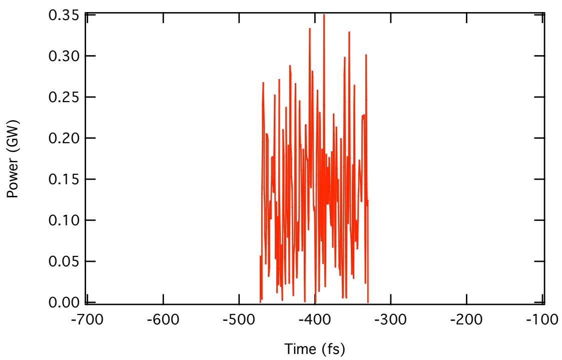
Seeded FEL

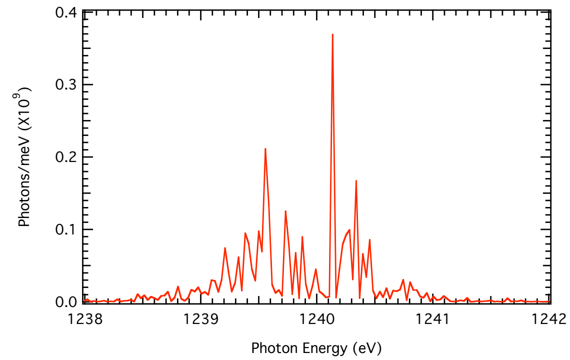
ENHANCED CAPABILITIES FOR CONTROL OF X-RAY PULSE

Pulse profile

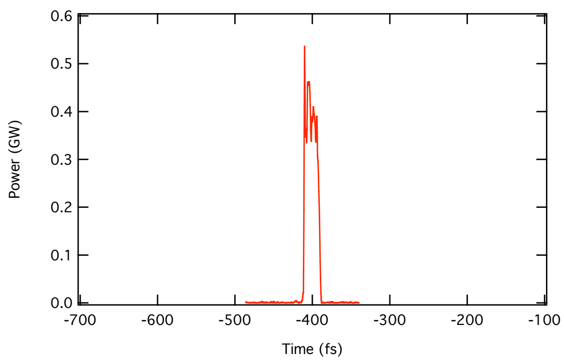
Spectrum

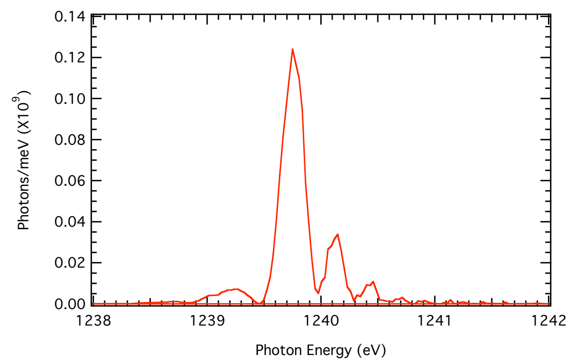
SASE



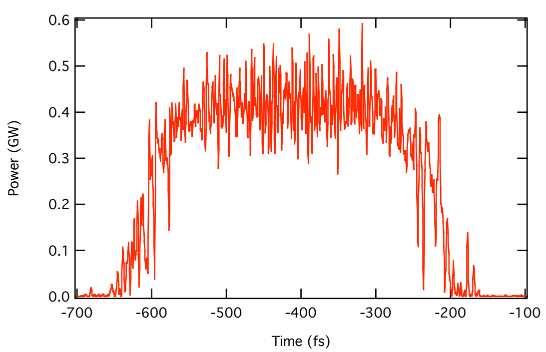


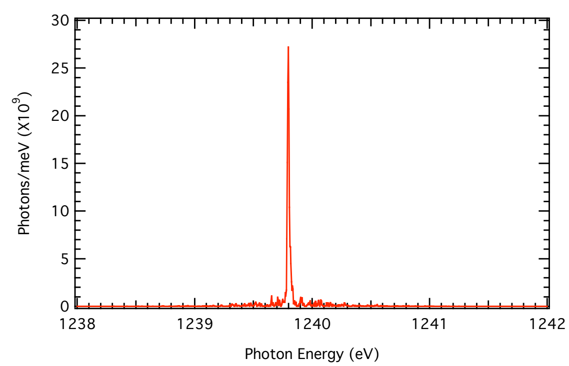
25 fs seed





500 fs seed

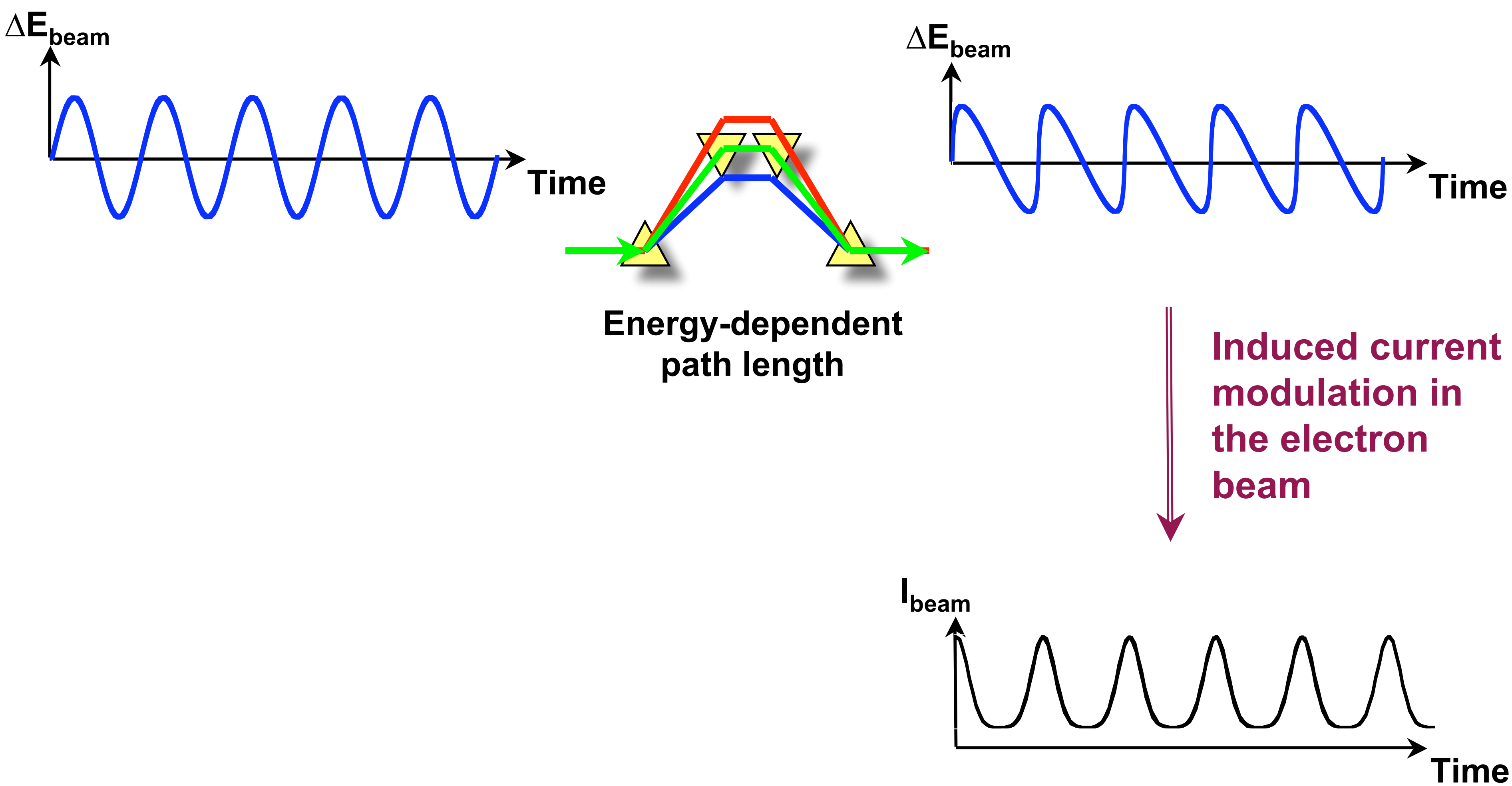




Electron beam is 1.5 GeV, energy spread 100 keV, 250 A current, 0.25 micron emittance; laser seed is 100 kW at 32 nm; undulator period 1 cm

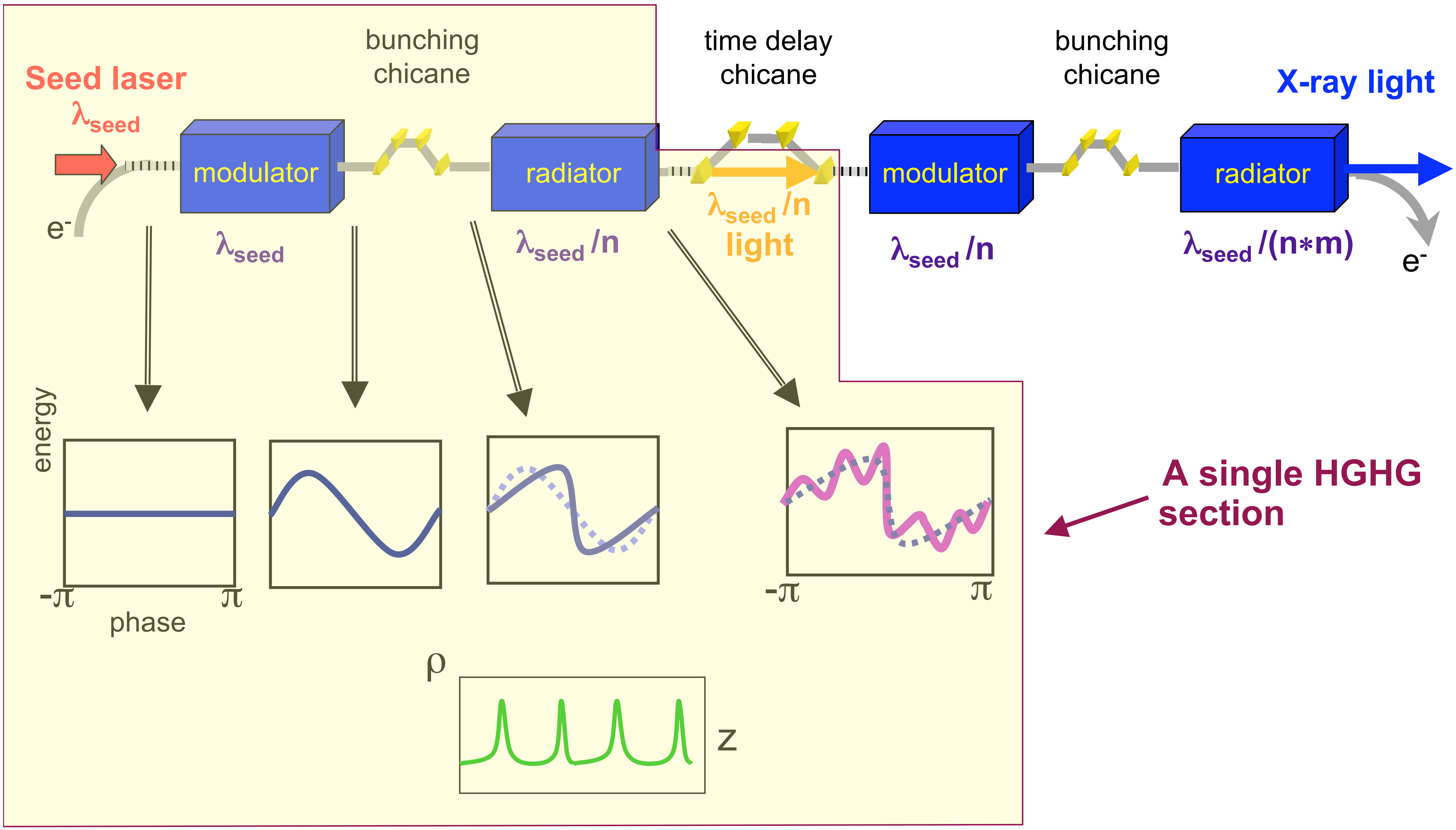
Bunching of the electron beam

ENERGY MODULATION FOLLOWED BY DISPERSIVE SECTION



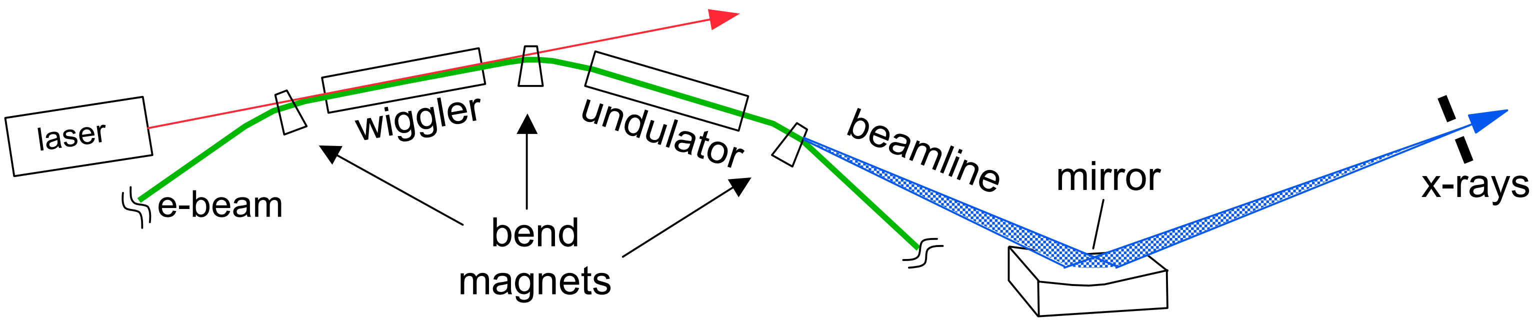
Harmonic cascade

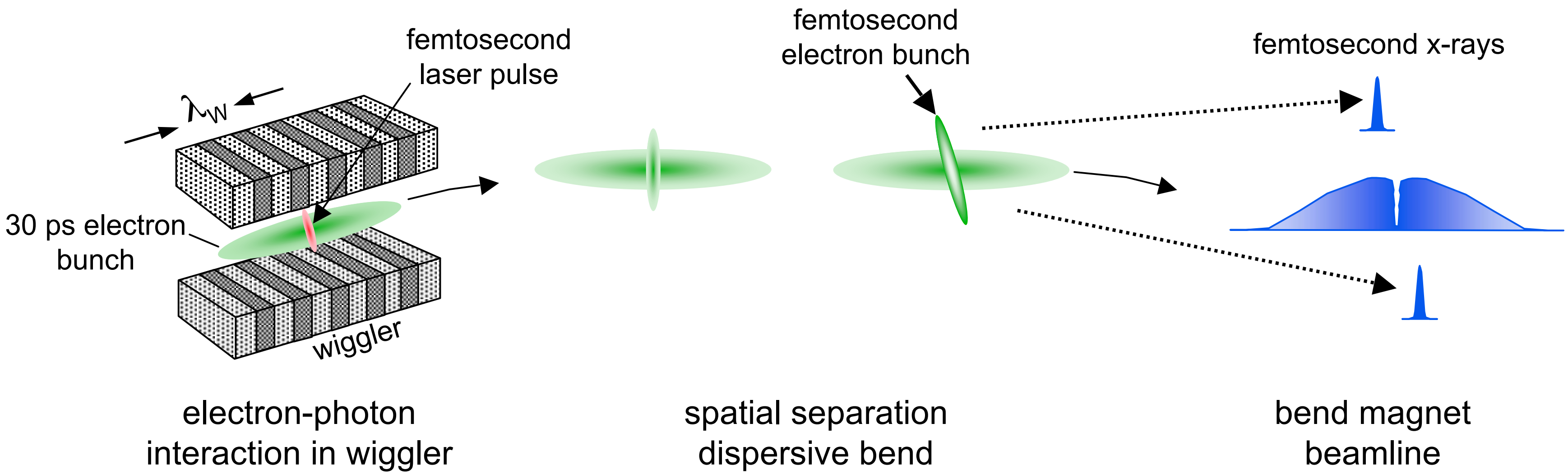
MULTIPLE STAGES TO REACH SHORTER WAVELENGTHS



Csonka 1980; Kincaid 1980; Bonifacio 1990; L.-H. Yu 1990

Laser-sliced x-ray pulses from synchrotrons are used as tunable soft and hard x-ray probes

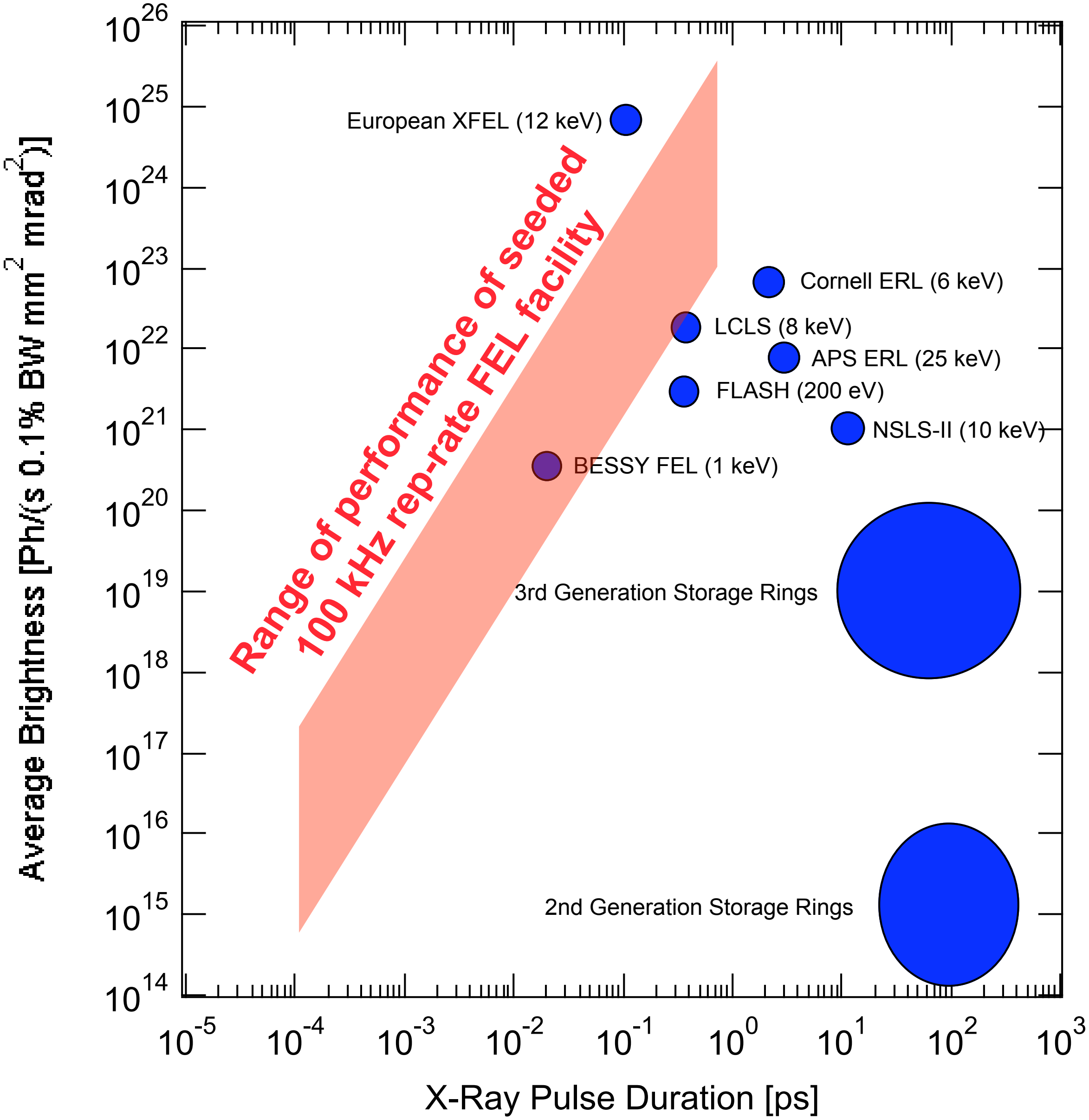




Zholents and Zolotorev, Phys. Rev. Lett., 76, 916,1996

New source performance comparison

TIME-DOMAIN RANGING FROM PICOSEC TO SUB-FEMTOSEC



Summary of integrated photon flux needed in condensed matter physics experiments

- angle resolved photoemission: volume datasets
  - 1e17 ph (20 – 100 eV)
- microscopy
  - 1e13 (280 – 1200 eV)
- spectro microscopy
  - 1e15 (280 – 1200 eV)
- time resolved microscopy
  - 1e16 ph (280 – 1200 eV)
- time resolved spectroscopy
  - 1e10 ph (280 – 1200 eV)

From H. Padmore

Workshop "High Average Power Lasers and High Harmonics"

December 12, 2007

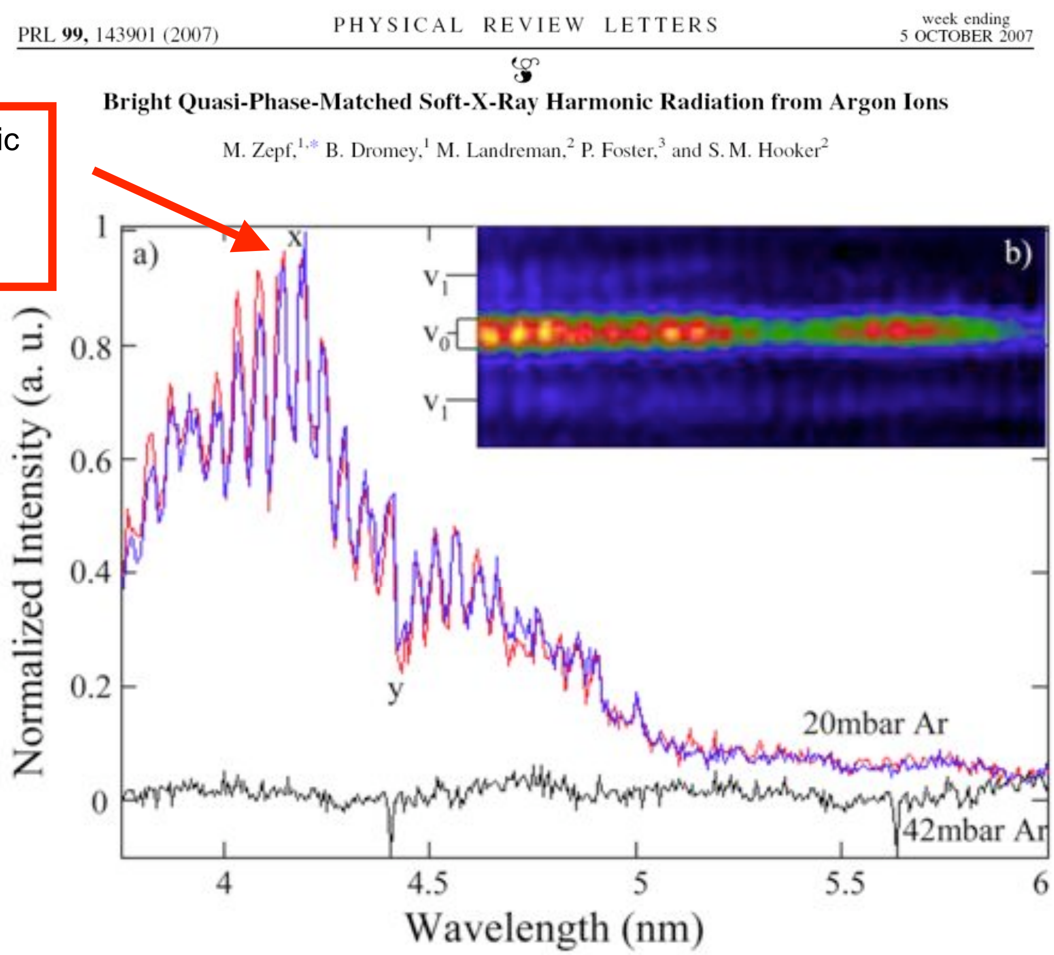
Discuss future possibilities for high average power lasers that could:

- drive high-peak and high-average power high-order harmonic sources
- be utilized for coherent soft x-ray science
- manipulate electron beams and seed FELs
- enable laser-based accelerators for applications including light sources

Quasi-phase matching at 300 eV in Ar

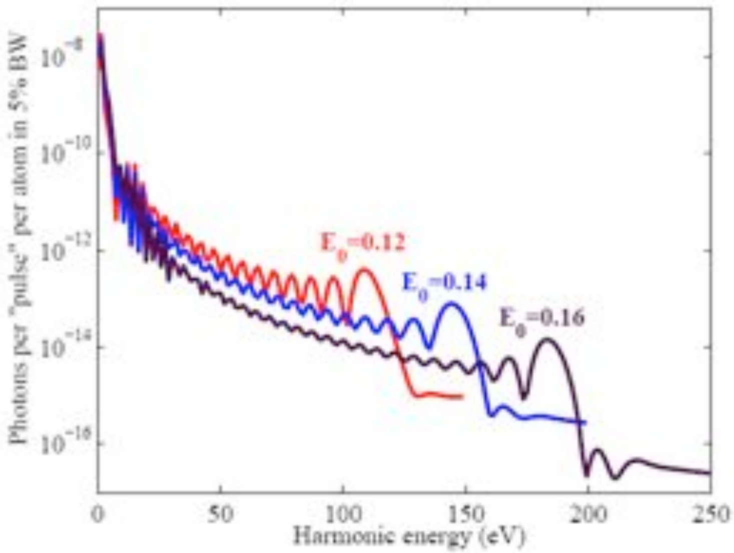
~ E9 photons/pulse/harmonic
@ 300 eV

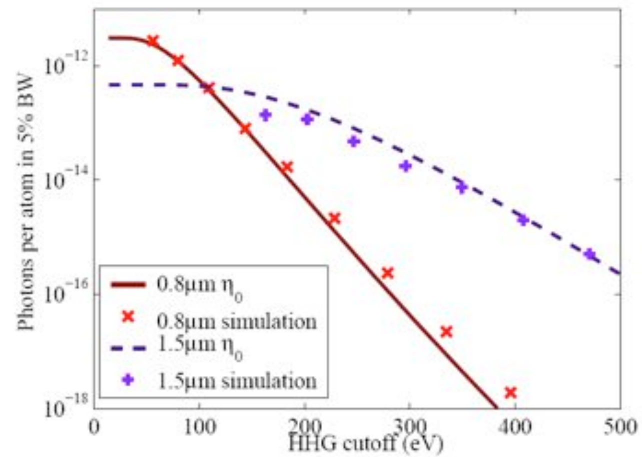
~ E12 photons/sec



- 5 mJ / pulse, 800 nm, 40 fsec
- focused to ~ 1e15W/cm^2 into 1 cm length Ar filled capillary

Optimized HHG at longer drive wavelengths

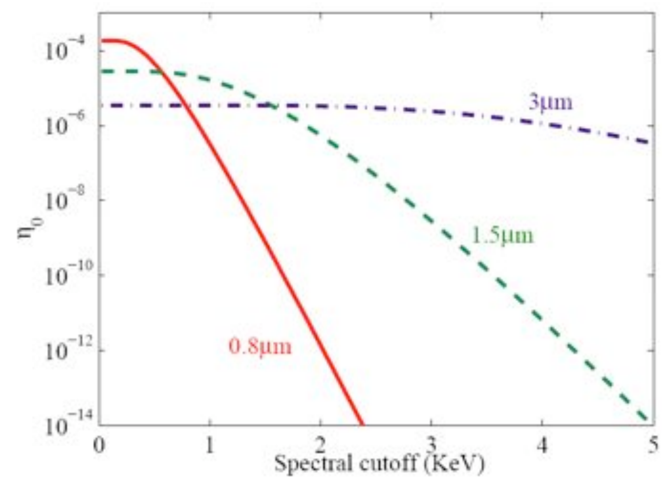




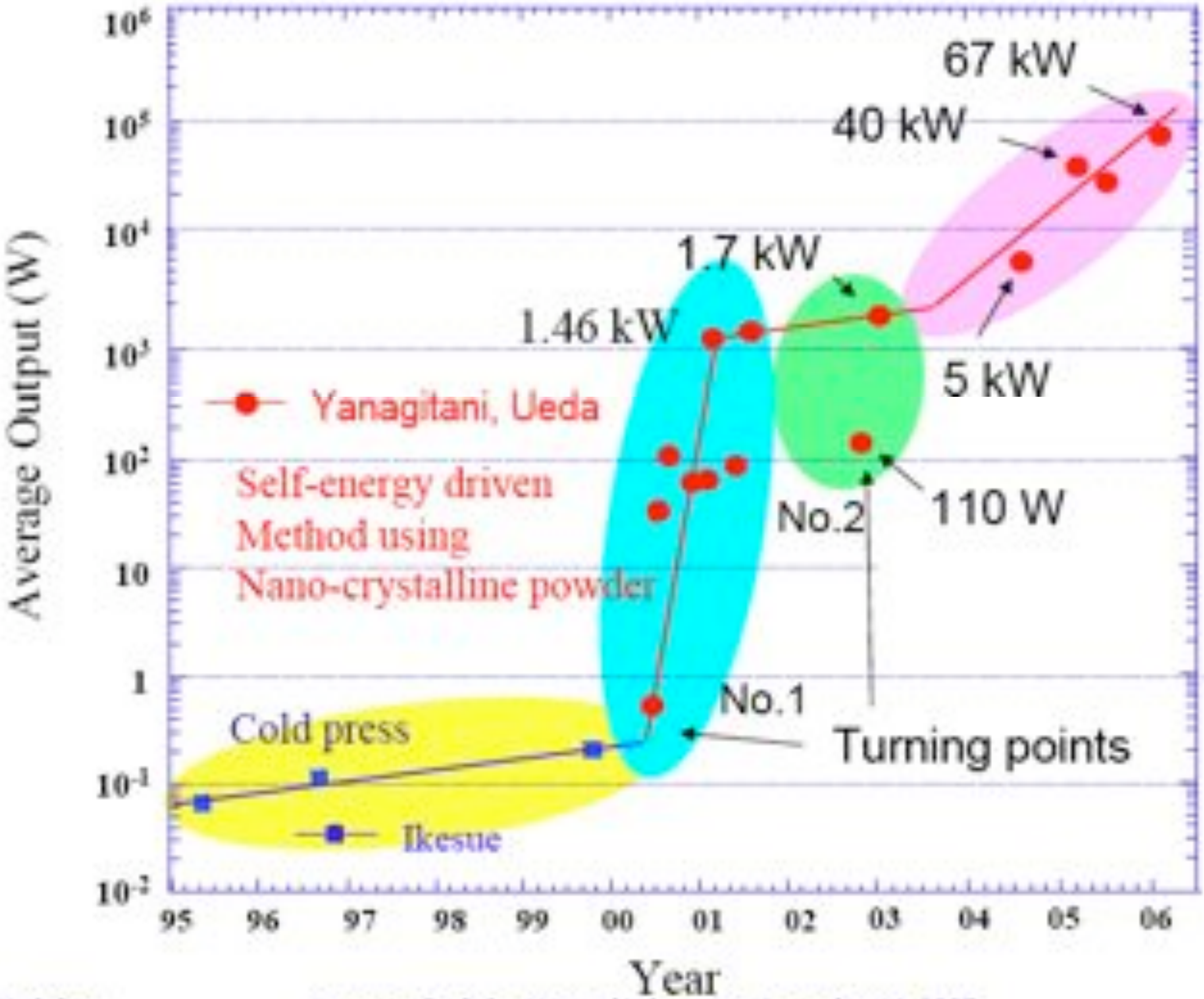
Scaling of keV HHG photon yield with drive wavelength

Ariel Gordon and Franz X. Kärtner

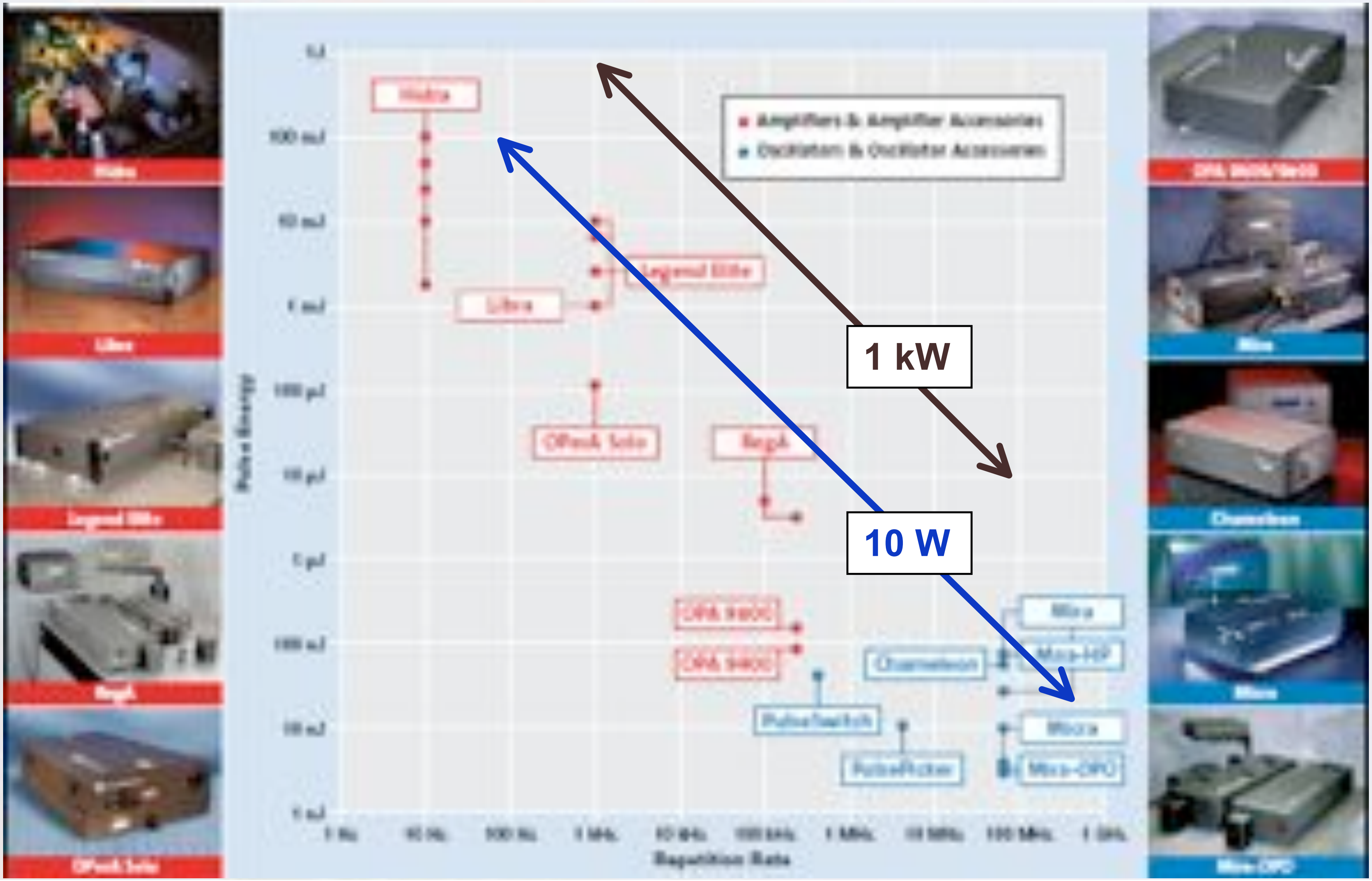
18 April 2005 / Vol. 13, No. 8 / OPTICS EXPRESS 2947



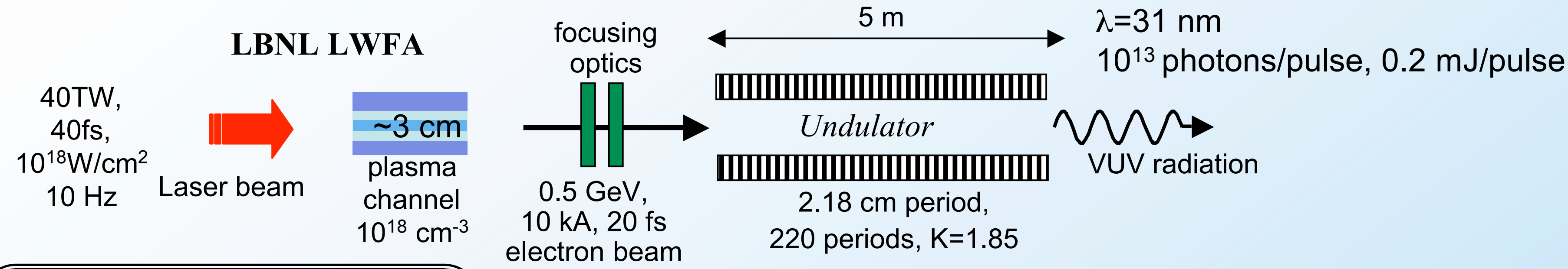
Rapid Progress of Ceramic Lasers
(Ken-ichi Ueda - FMK1 Oct 9 2006)



Largest Selection of Ultrafast Lasers

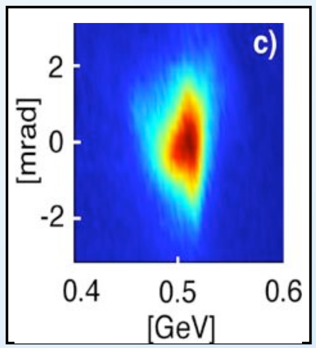


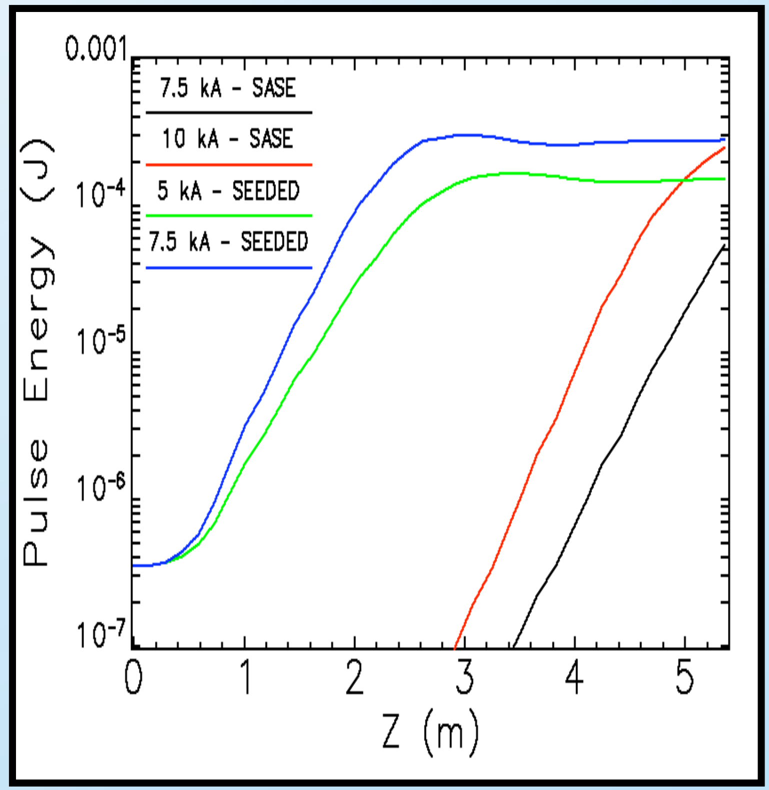
LWFA-driven coherent VUV source



LWFA Electron Beam:

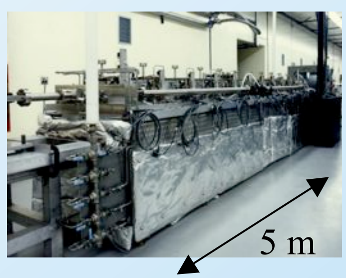
Beam Energy	0.5 GeV
Peak current	10 kA
Charge	0.2 nC
Bunch duration, FWHM	20 fs
Energy spread (slice)	0.25 %
Norm. Emittance	1 mm-mrad





Undulator Parameters:

Undulator type	planar
Undulator period	2.18 cm
Number of periods	220
Peak Field	1.02 T
Undulator parameter, K	1.85
Beta function (0.5 GeV)	3.6 m



Leemans, et al (LBNL) Collaboration with MPQ, Germany

Conclusions

- Grand Challenge science requires a range of new x-ray sources
- FLASH, LCLS, the ALS-slicing beamline, APS time-resolved beamlines, etc. are growing new communities of scientists interested in the time domain
- designs exist for high-power x-ray FELs, with flexible parameters and multiple beamlines; R&D is needed
- lasers and high harmonics will have sufficient power for compelling experiments and for seeding coherent, x-ray FELs; R&D is needed
- … but lasers (even at kW average powers and mW high-harmonics) and crab/slicing sources will not rival average soft and hard x-ray power from FELs, which have mA currents, GeV energies, and watts of coherent x-rays for Grand Challenge experiments
- Crabing and slicing sources have comparable flux to laser harmonics in the soft x-ray, and greater flux in the hard x-ray
- novel accelerator schemes may eventually become available to drive electron accelerators for light source applications